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RESEARCH MEMORANDUM

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AXIAL-FLOW COMPRESSOR

By Howard F. Calvert, André J. Meyer, Jr. and C. Robert Morse

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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By authority of 4 RN-120 Date 9-13-57
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INVESTIGATION OF BLADE FAILURES IN A J34, ELEVEN-STAGE

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SUMMARY

A vibration survey was conducted during normal operation of a production eleven-stage axial-flow compressor powered as part of a complete turbojet engine. After a serious third-stage vibration was detected, a systematic investigation was conducted to study and eliminate the vibration with various engine component configurations. Curves presented herein show the effect of these variations of engine component geometry on the vibration amplitude and engine performance.

The source of excitation was determined to be an aerodynamic phenomenon possibly related to stall. A new inlet-guide-vane assembly with a 4-percent increase in inlet area eliminated the critical third-stage vibration and increased the engine thrust 4 percent.

INTRODUCTION

The Bureau of Aeronautics, Department of the Navy, reported blade failures in a production eleven-stage axial-flow compressor in a turbojet engine; therefore, the NACA Lewis Laboratory conducted a fundamental research program to determine the general cause of blade failures in axial-flow compressors. The failures were primarily in the third rotor stage and usually occurred at a speed slightly below the normal cruising speed; some occurred after a few hours of operation, others after long periods. However, only a few of the total number of engines produced gave trouble, the majority completing useful lives without blade failures. The same model turbojet engine in which failures had been reported was used for this investigation.

The investigation consisted in instrumenting the compressor rotor blading with resistance-wire strain gages and operating the complete engine under normal operating conditions. After the critical third-stage vibration was detected, a systematic investigation was conducted to determine its source and find a means of correcting the condition.

Data showing the effect of changing the angle of incidence of blades in the second stators, the inlet guide vanes, and the third-stage rotor blades on the vibration and engine performance are reported herein.

APPARATUS AND PROCEDURE

Commercial resistance-wire strain gages were cemented to the rotating compressor blades of a production J34 turbojet engine, and the lead wires were brought through the rotor and connected to a 19-ring slip-ring assembly as described in references 1 to 3. The instrumented blades were grouped in two axial lines approximately 180° apart. Two slip-ring assemblies were used. One unit was wired to transmit simultaneously strain-gage signals from one blade in each stage of the compressor except in stage three, where the signals from two blades were transmitted. The second unit was wired to transmit signals from twelve blades in the first three stages. A 12-channel recording oscillograph was used to record permanently the strain-gage signals and a timing trace which indicated each revolution of the compressor. From these records the frequency, excitation order, and stress amplitude of the vibrations; the phase relation between vibrating blades; and the rotational speed at which the vibrations occurred could readily be determined.

The engine was operated throughout the normal speed range of 5000 to 12,500 rpm in order to observe all blade vibrations present. The investigation was conducted with the turbojet engine operating in two different test cells. First, the engine was operated in a turbojet altitude chamber (fig. 1) where the air supply and exhaust were connected to the laboratory systems. Second, the engine was operated in a sea-level test stand where the air supply was taken from the surrounding atmosphere and exhausted through a muffler to the atmosphere. All engine parts were fabricated by the engine manufacturer and sent to the Lewis laboratory.

Altitude Test Chamber

In the altitude test chamber the strain-gage installation included three instrumented blades in each stage except the first and third stages, which had four and five gages, respectively. During the first operation of this investigation, a serious third-stage vibration was observed around 9000 rpm. All the research thereafter was concentrated on obtaining an understanding of and a means of eliminating this vibration. The procedures used in investigating this vibration are discussed in the following paragraphs.

Accessory case removal. - Frequently vibrations are mechanically excited. A possible source of excitation of blade vibration is the accessory drive. Therefore, the accessory drive was removed from the engine, and the engine was windmilled; the laboratory combustion air and altitude exhaust were used.

Accessory case installed. - The accessory drive was again assembled to the engine, which was operated under power up to 10,500 rpm, at which point the fuel supply was shut off. As the engine speed decreased through the critical speed range, the strain-gage signals were observed. If the source of vibration were mechanical excitation from the accessory drive gearbox, the vibration should be present with or without combustion.

Combustion cycling. - Combustion cycling could be another source of excitation. Strain gages were mounted on the combustion-chamber housing and the engine operated throughout the critical speed range.

Hot-wire anemometer. - A hot-wire anemometer was installed in the compressor stators just ahead of the third stage. The fluctuation of air velocity at some frequency with a relation to the frequency of the blade vibration would be another definite source of excitation.

Torsional rotor vibrations. - In any assembly of mechanical equipment composed of two or more masses connected by shafting such as the compressor and the turbine of a turbojet engine, there is always a possibility of torsional vibration between the sections. A torsigraph was installed at the front of the compressor to detect any torsional vibration present in this assembly.

Inlet valve. - A special valve assembly (fig. 2) was fabricated to control the air flow to one-half of the compressor inlet from approximately zero to full flow. This valve simulated possible uneven air-flow conditions of the two-duct inlet-air supply system used in many aircraft and was used to determine the effect of flow pattern on vibration.

Inlet duct. - The section of inlet ducting containing the special valve was fabricated in two parts (fig. 2). The top half of the duct and the special valve were removed, and the engine was operated throughout the critical speed range. With the duct open the engine was receiving its air from the test cell. This procedure was carried out to determine the effect of the laboratory inlet piping on the vibration.

Sea-Level Test Stand

The engine was also operated in a sea-level-type test stand. New instrumentation was installed on the compressor blading, with two instrumented blades on all except the first, second, and third stages, which had three, three, and six instrumented blades, respectively. The same slip-ring assemblies were used as in the first investigation. Air to the compressor was drawn from the surrounding atmosphere, and the exhaust was discharged through an open muffler to the atmosphere.

Again the serious third-stage vibration was detected and an investigation was conducted as discussed in the following paragraphs.

Various exhaust nozzles. - The compressor pressure ratio was varied by installing fixed-area exhaust nozzles with areas of 187, 176, 168, and 150 square inches. After each nozzle had been installed, the engine was operated throughout the critical speed range in order to determine its effect on the vibration.

Pressure-rise tests. - Static wall pressure taps were installed before and after the third stage to determine whether there was a pressure rise across the third stage at all times and thus detect any stalling in this stage in the critical speed range.

Measuring probes. - An NACA probe actuator was installed on the compressor housing over the third stator row, so that various measuring probes could be inserted 1/4 inch from the trailing edge of the third-stage rotor blades. A hot-wire anemometer and a thermocouple rake were installed in the actuator to make a radial survey of the air-flow characteristics throughout the critical speed range.

Stator blades. - Twisting or changing the angle of incidence of stator or rotor blades is a common standard means of attempting to solve such air-flow problems as compressor stall. A series of second-stage stators were fabricated by the engine manufacturer with various angles of incidence (fig. 3). These angles are shown in table I.

Inlet guide vanes. - A new inlet-guide-vane assembly (fig. 4) was fabricated by the manufacturer with a decreased angle of incidence of the vanes, which resulted in a 4-percent increase in the inlet flow area. This new inlet was operated with all the second-stage stators listed in table I.

Rotor blades. - Two new sets of third-stage rotor blades were installed and operated with the standard inlet guide vanes and second-stage stators. The new rotor blades had increases in the angle of incidence of 6° and 12° .

All these various configurations were installed in the engine and operated throughout the normal speed range, and their effect on the third-stage vibration was determined.

RESULTS AND DISCUSSION

During the initial part of this investigation a serious first-bending-mode blade vibration in the third stage of the compressor was observed and recorded. A maximum vibratory stress of $\pm 42,000$ pounds per square inch was measured in the altitude chamber. The order of this vibration corresponded to 2.63 cycles per revolution and occurred at 9250 rpm; however, this

order number eliminates such exciting forces as caused by the four struts of the front bearing support and other evenly spaced obstructions. The engine rotational speed at which failures had been known to occur, 9300 rpm, correlates with the speed at which this unusually high-amplitude vibration was observed.

Early in the investigation certain interesting characteristics of this vibration were noted. Close examination of the record showed that as the engine speed was gradually increased or decreased through the critical speed range, all the instrumented blades in the first three stages were vibrating at the same frequency. Furthermore, all these blades were bending in phase. As a result of the spread in the natural frequencies of the instrumented blades, the peak vibrations were recorded over a speed range of 600 rpm; however, each blade reached its peak amplitude when the product of the rotor speed in revolutions per second and vibration order equalled the natural frequency of the blade. The maximum vibratory stress was recorded in the third stage.

Accessory case removal. - Using the complete capacity of the laboratory combustion air and exhaust systems, the operators were unable to windmill the engine through the critical speed range to determine whether the vibration was present without the accessory drive case.

Accessory case installed. - The accessory drive case was assembled in the engine. The vibration was present throughout the critical speed range as the engine was accelerated or decelerated with combustion maintained. The engine was accelerated up to 10,500 rpm and the fuel supply shut off. As the engine speed decreased through the critical speed range no vibration was present, which indicated that the source of this excitation was aerodynamic. If the source were mechanical, the vibration would be present with or without combustion. Without combustion the compressor pressure ratio is a minimum at any engine speed. Many investigators (see reference 1) have reported a reduction in vibratory stress with a reduction in pressure ratio as indicated with this investigation.

Combustion cycling. - The engine was operated throughout the critical speed range and the strain-gage signals on the combustion chamber were observed. No combustor vibration was present with characteristics for exciting the blade vibration.

Hot-wire anemometers. - With the hot-wire anemometer installed, the jet engine was operated throughout the critical speed range. The air velocity could be fluctuating at a frequency equal to or at some multiple of the vibration frequency; however, no velocity fluctuations with such a frequency were observed.

Torsional rotor vibrations. - As the engine was operated throughout the critical speed range, the torsionograph signals were carefully examined

for any vibration; however, no torsional vibration was present which was capable of exciting the compressor blading.

Inlet valve. - With the inlet valve at various positions from open to fully closed, the engine was accelerated and decelerated throughout the normal speed range. The strain-gage signals were closely observed, but the position of the inlet valve did not affect the third-stage-vibration amplitude nor introduce any new vibration.

The valve position had a decided effect on engine performance. Figure 5 presents curves of the compressor efficiency, pressure ratio, and corrected air flow, and corrected engine thrust plotted against corrected engine speed. Operating with the closed valve reduced the corrected engine thrust approximately 9 percent. Such a loss in thrust would be serious; however, for the jet-engine installation with the twin-inlet-duct system the airplane could have one duct damaged or filled with foreign material during a flight with little or no effect on the ability of the airplane to return to its base.

Inlet duct. - When the engine was operated with the top half of the inlet duct removed, the critical third-stage vibration was completely eliminated. The top half of the inlet was again installed and the engine operated. Again the critical third-stage vibration was present. These results indicate that the inlet ducting system could be either causing or aggravating this vibration.

Sea-Level Test Stand

The jet engine operating in the altitude chamber indicated that the excitation force was aerodynamic. Operation with a closed inlet system produced extremely high vibration, whereas operation with an open system completely eliminated the vibration. Therefore, new strain gages were applied to the compressor for installation in the jet engine, and the engine was installed in a sea-level test stand. Here the air supply and exhaust were completely independent of any external system.

The engine was started and operated throughout the critical speed range with the critical third-stage vibration once again present, which indicated that the piping system of the turbojet altitude chamber was not the source of excitation. However, the vibratory stress amplitude in the sea-level test stand was approximately one-half that present at the first-setup. That is, the vibratory stress measured was $\pm 22,000$ pounds per square inch at the sea-level test stand and $\pm 42,000$ at the jet-engine altitude chamber.

Various exhaust nozzles. - The effect of exhaust-nozzle area on the third-stage blade vibration is presented in figure 6. As the nozzle area was reduced and the pressure ratio increased, the vibratory stress increased. This same effect was observed and reported in reference 1. The 168-square-inch nozzle was the standard for the investigation.

Pressure-rise test. - The third-stage static-pressure rise at equivalent engine speeds from 7500 to 12,000 rpm is shown in figure 7. A constant rate of pressure rise with engine speed was observed at all speeds except in the critical speed range from 8500 to 9500 rpm. Here the pressure remained approximately constant for about 1000 rpm, which indicated that the third stage was probably in a partially stalled condition.

Temperature and hot-wire measuring probes. - Data from the temperature survey of the air out of the third stage are plotted in figure 8. At all speeds the temperature increased uniformly from the base to the tip of the blade except from 1 to 2 inches from the hub at 9000 rpm. This 10° rise and the consistently high temperature at the blade tip indicate that stalling possibly exists around the lower part of the blade at 9000 rpm and at the tip throughout the complete critical speed range.

A hot-wire anemometer was installed in the probe actuator and the engine again operated throughout the critical speed range. The hot-wire anemometer, an instrument capable of measuring fast velocity changes, was inserted into the air stream to determine whether the air from the third stage was fluctuating at some frequency related to the frequency of the blade vibration. The hot-wire anemometer was used in reference 4 to detect a stall phenomenon referred to as rotating stall, which has been known to excite blade vibration; however, data obtained from this anemometer were insufficient to indicate rotating stall. The hot wire detected the wakes from the rotating blades, and velocity fluctuations not at wake frequency near the rotor tip.

Stator blades. - An investigation of the effect of the angle of incidence of the stator vanes immediately preceding the third stage of the compressor was conducted in a sea-level test stand; the results are shown in figure 9. The vibratory stress levels noted on this plot are averages of numerous data points of the maximum amplitude obtainable in the critical speed range for each stator angle. The number of stator assemblies tested for each angle, the resulting average stress, and the percentage of the stress produced by the standard vanes are presented in table I.

Installation of the stator with vanes closed 3° reduced the vibratory stress to less than half and would possibly bring the vibration below the danger point. A change, however, to 9° greater angle of incidence would assuredly eliminate all third-stage vibration failure of this compressor design in the critical speed range. However, with the 9° -closed

configuration there was a $3\frac{1}{2}$ -percent loss in engine thrust at military take-off.

The complete speed range (to 12,500 rpm) was investigated with vanes of each angle to determine vibratory effects as well as engine performance. No new vibration of significant amplitude was introduced by any of the new angles. The effect on over-all engine performance is illustrated in figures 10 and 11. Although a total change of 18° (6° open to 12° closed) was investigated, very little change in engine performance was detected.

Inlet guide vanes. - It was decided to investigate the effect of opening the compressor-inlet flow area to increase the weight flow and engine thrust. The manufacturer supplied new inlet guide vanes (fig. 4) with an increase in flow area of approximately 4 percent. The vanes were installed in the engine and the engine operated throughout the complete speed range. The operation with the new inlet guide vanes and standard second-stage stators indicated that the serious third-stage vibrations had been eliminated and no new vibration introduced. A check of the engine thrust at military take-off showed that the change in inlet guide vanes had increased the thrust approximately 4 percent, or an increase of $7\frac{1}{2}$ percent over the operation with the 9° -closed stators.

Rotor blades. - The effect of twisting the third-stage blades on the third-stage vibration was considered. The manufacturer fabricated two sets of third-stage rotor blades with increased angle of incidence and supplied them to the laboratory. These blades had increased angles of incidence of 6° and 12° . The blades were installed in the compressor and the engine operated throughout the complete speed range. Three of the 25 blades were not replaced, since their removal would damage the strain-gage instrumentation for the stage. However, three of the twisted blades had strain-gages applied to their surface and were an active part of the instrumentation. Compressor operation showed that the 6° twisted blades vibrated with a stress of ± 7300 pounds per square inch, or a reduction of approximately 66 percent over the standard blades. The 12° twisted blades eliminated the third-stage vibration completely, but introduced a first-stage vibration of $\pm 12,150$ pounds per square inch at military take-off. Without further research, twisting the third-stage rotor blades is not a satisfactory means of eliminating the third-stage vibration.

SUMMARY OF RESULTS

From the analysis of oscillograph records and engine data, the following results were obtained:

1. The source of excitation for the serious third-stage vibration was aerodynamic.

2. Inlet ducting can affect engine vibration.

3. Of the stator vane assemblies tested with varied angles of incidence, the installation with vanes closed 9° produced the lowest vibration amplitude of the third-stage rotor blades, but with a $3\frac{1}{2}$ -percent loss in engine thrust at military take-off.

4. A change of 18° in second-stage stators had little effect on over-all engine performance.

5. The inlet-guide-vane assembly with an increase of 4 percent in the inlet flow area eliminated the third-stage vibration and increased the thrust 4 percent.

6. Twisting the third-stage rotor blades was not a satisfactory means of eliminating the third-stage vibration.

7. The 12° twisted third-stage blades introduced a new first-stage vibration at military take-off conditions.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

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1. Meyer, André J., Jr., and Calvert, Howard F.: Vibration Survey of Blades in 10-Stage Axial-Flow Compressor. II - Dynamic Investigation. NACA RM E8J22a, 1949. (Supersedes NACA RM E7D09.)
2. Meyer, André J., Jr., and Calvert, Howard F.: Vibration Survey of Blades in 10-Stage Axial-Flow Compressor. III - Preliminary Engine Investigation. NACA RM E8J22b, 1949. (Supersedes NACA RM SE8A28.)
3. Meyer, André J., Jr., Calvert, Howard F., and Morse, C. Robert: Effects of Obstructions in Compressor Inlet on Blade Vibration in 10-Stage Axial-Flow Compressor. NACA RM E9L05, 1950.
4. Huppert, Merle C.: Preliminary Investigation of Flow Fluctuations During Surge and Blade Row Stall in Axial-Flow Compressors. NACA RM E52E28, 1952.

TABLE I - SUMMARY OF VIBRATORY STRESS WITH
VARIOUS STATOR ASSEMBLIES

Angle of incidence (deg)	Vane assemblies investigated	Average vibratory stress in third-stage blades (psi)	Percent of standard stress
6 Open	3	$\pm 10,700$	62.0
0 Standard	2	$\pm 17,250$	100.0
3 Closed	1	$\pm 8,350$	48.4
6 Closed	5	$\pm 4,550$	26.4
9 Closed	1	$\pm 1,600$	9.3
12 Closed	3	$\pm 2,400$	13.9

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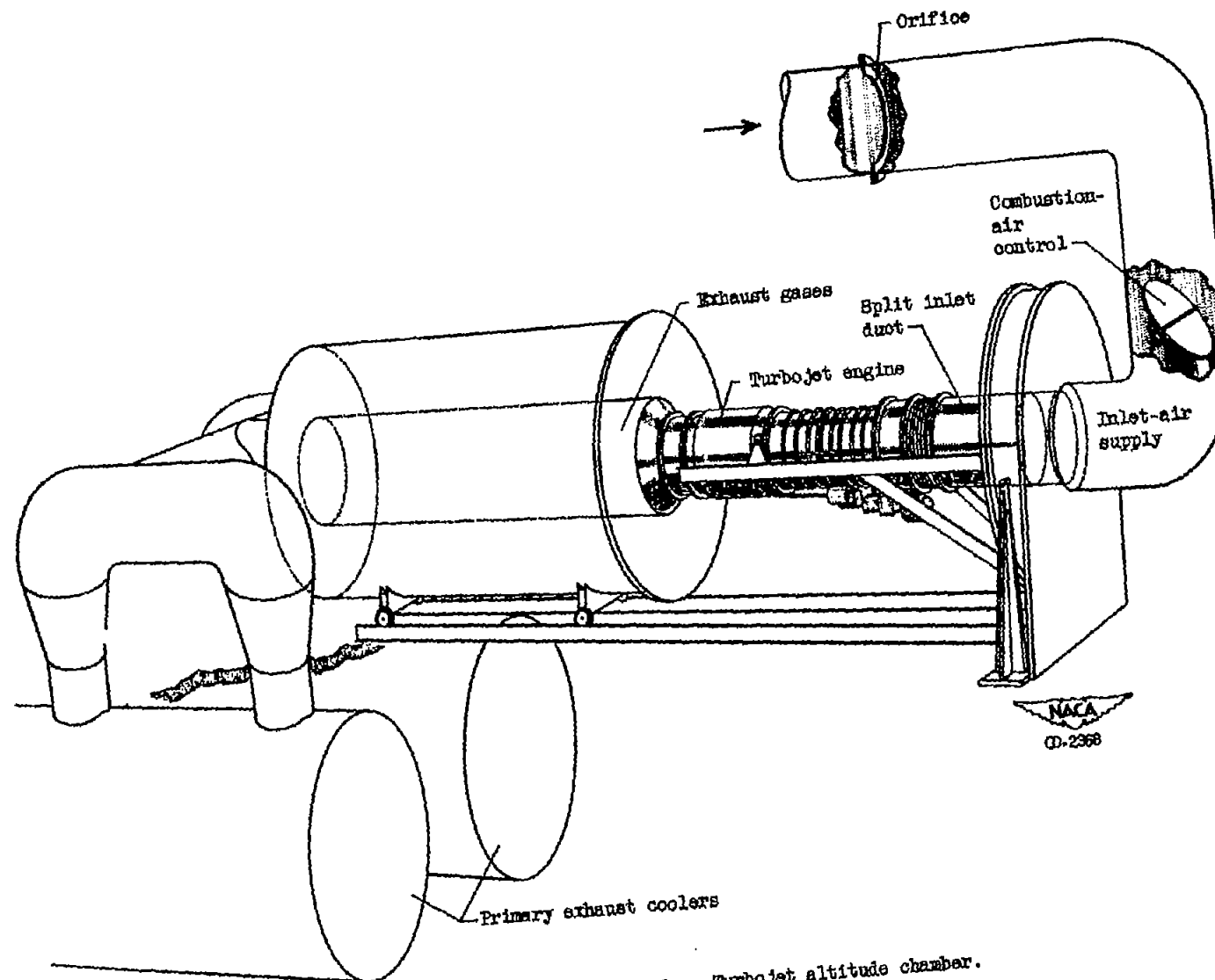


Figure 1. - Turbojet altitude chamber.

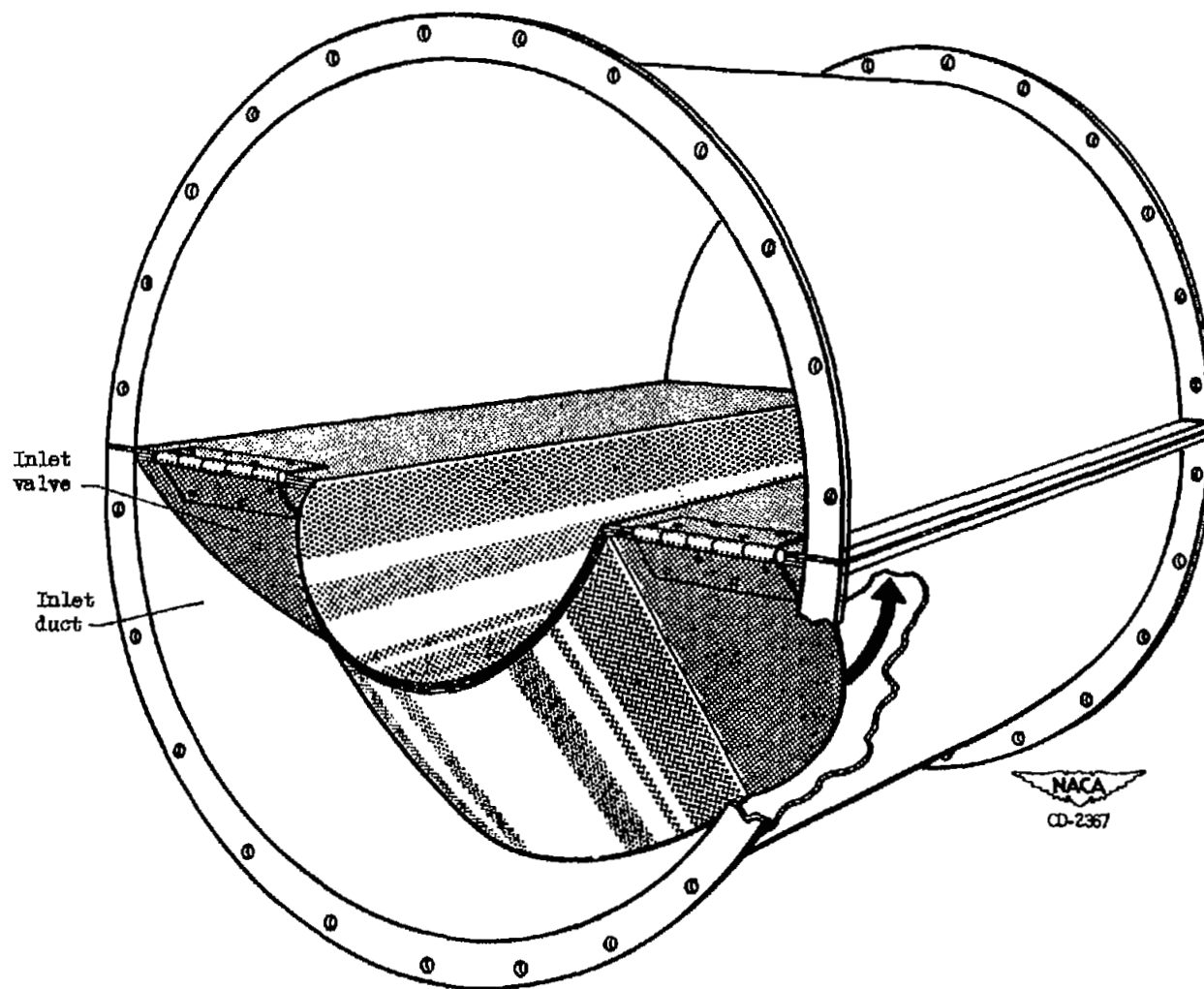
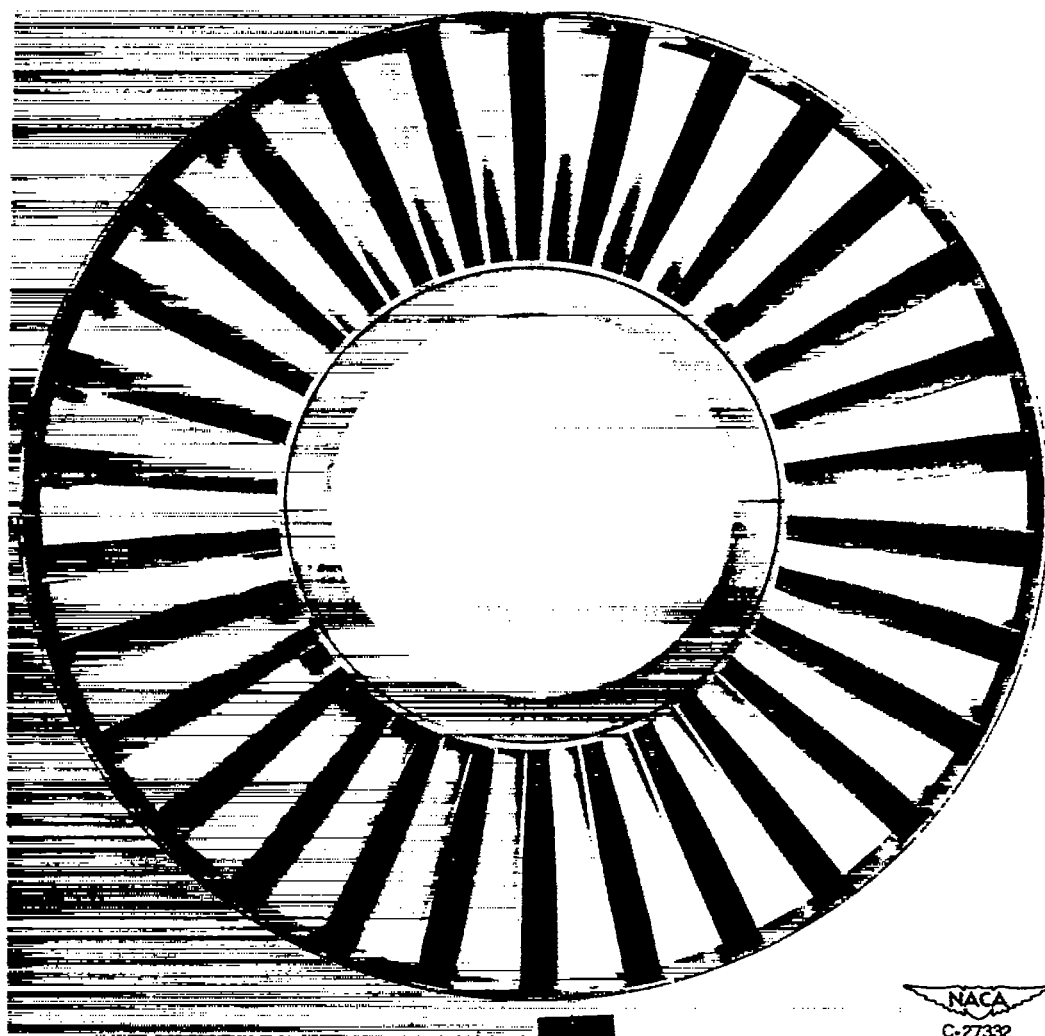


Figure 2. - Split inlet duct and inlet valve.



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Figure 3. - Second-stage stator vane.

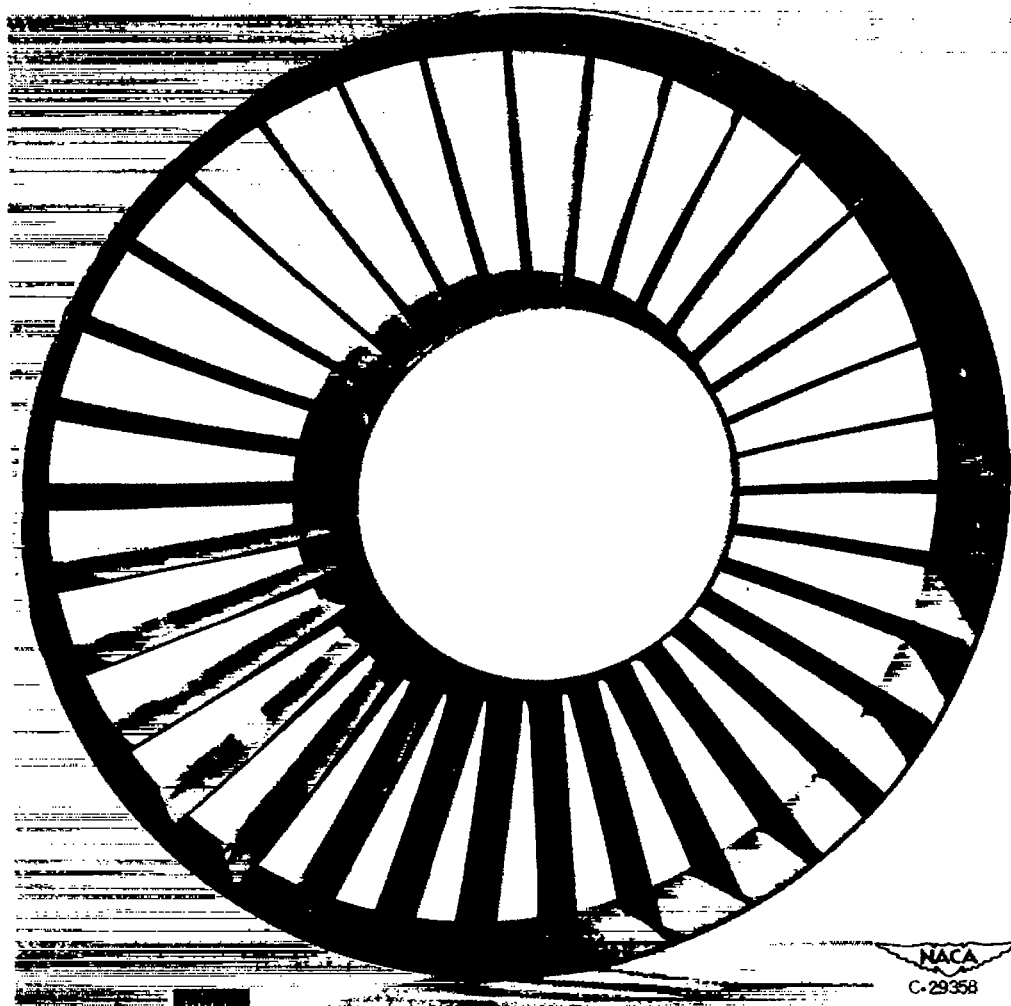
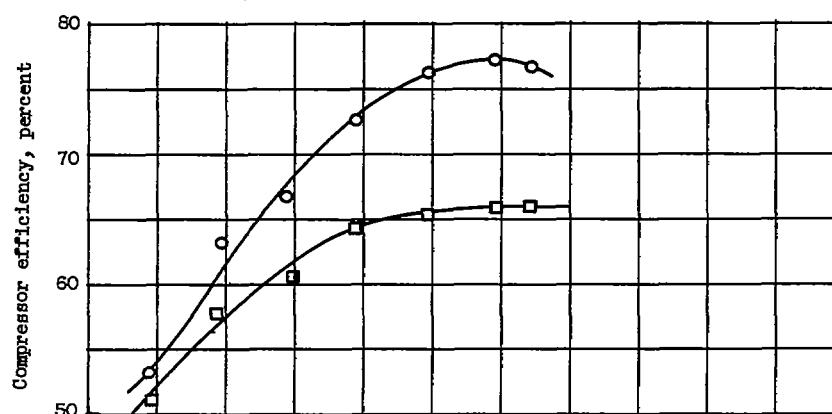
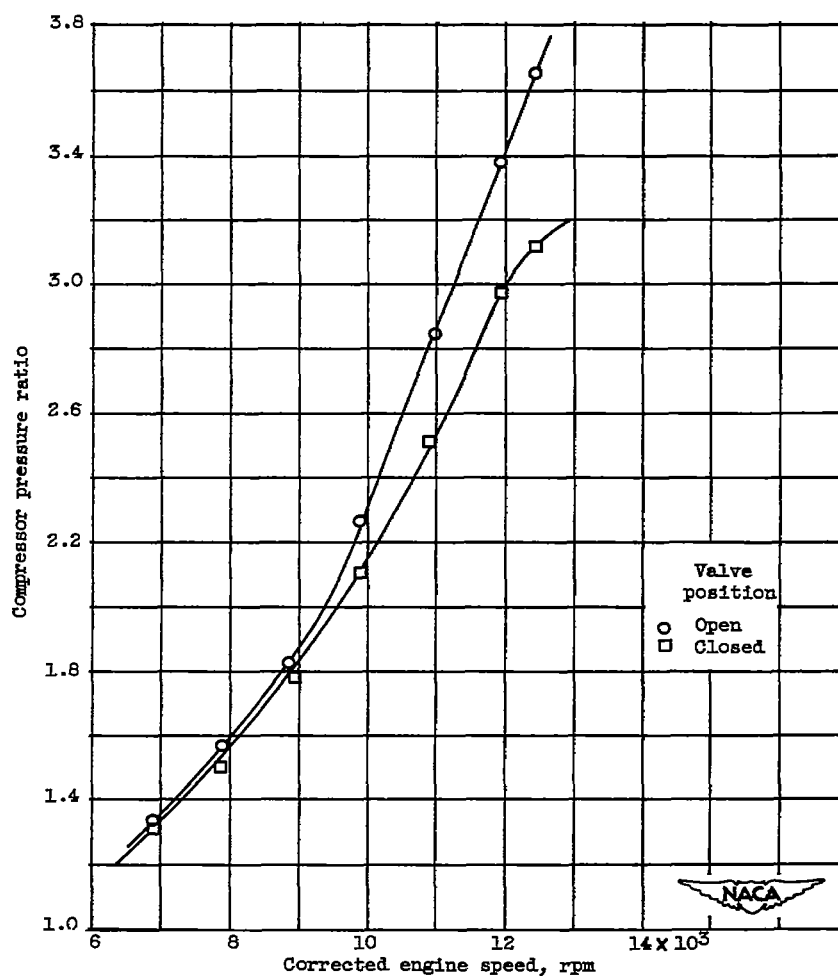


Figure 4. - Inlet guide vane.

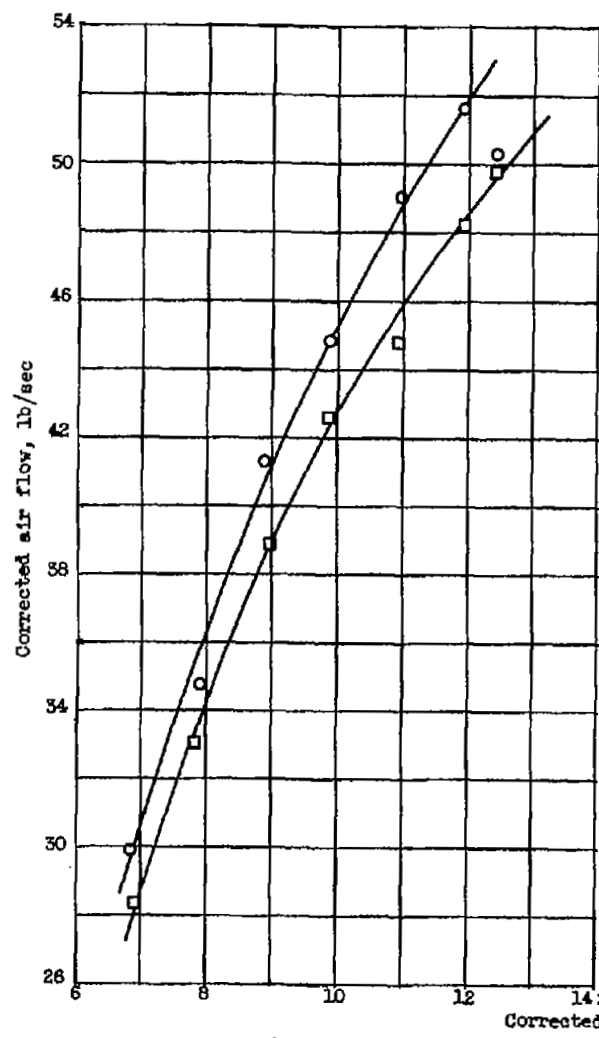


(a) Compressor efficiency.

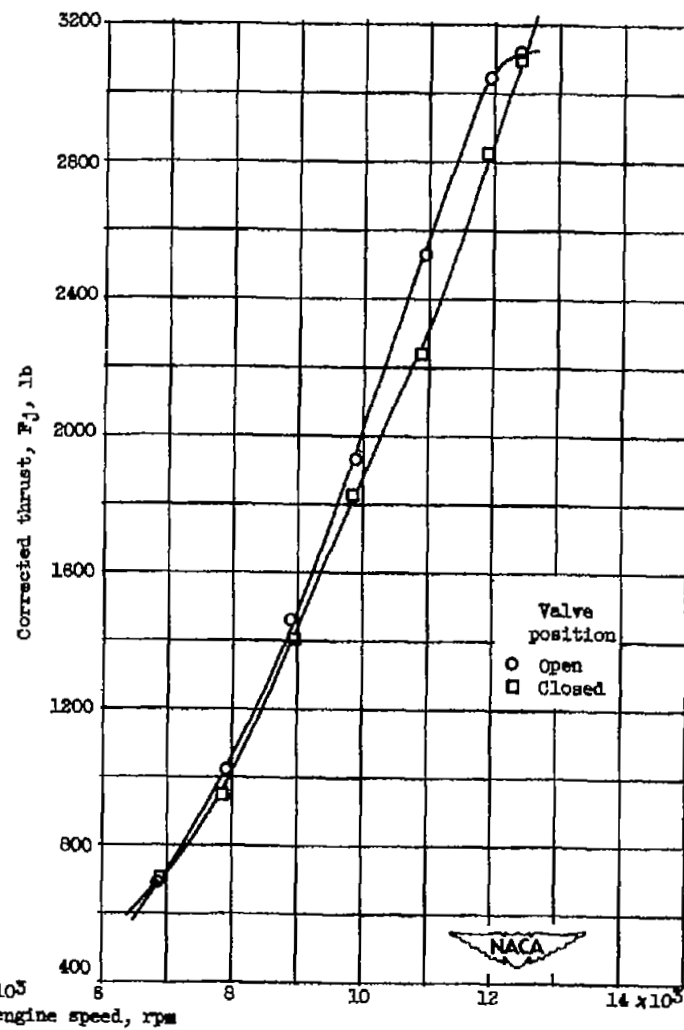


(b) Pressure ratio.

Figure 5. - Effect of inlet-valve position on engine performance.



(c) Air flow.



(d) Engine thrust.

Figure 5. - Concluded. Effect of inlet-valve position on engine performance.

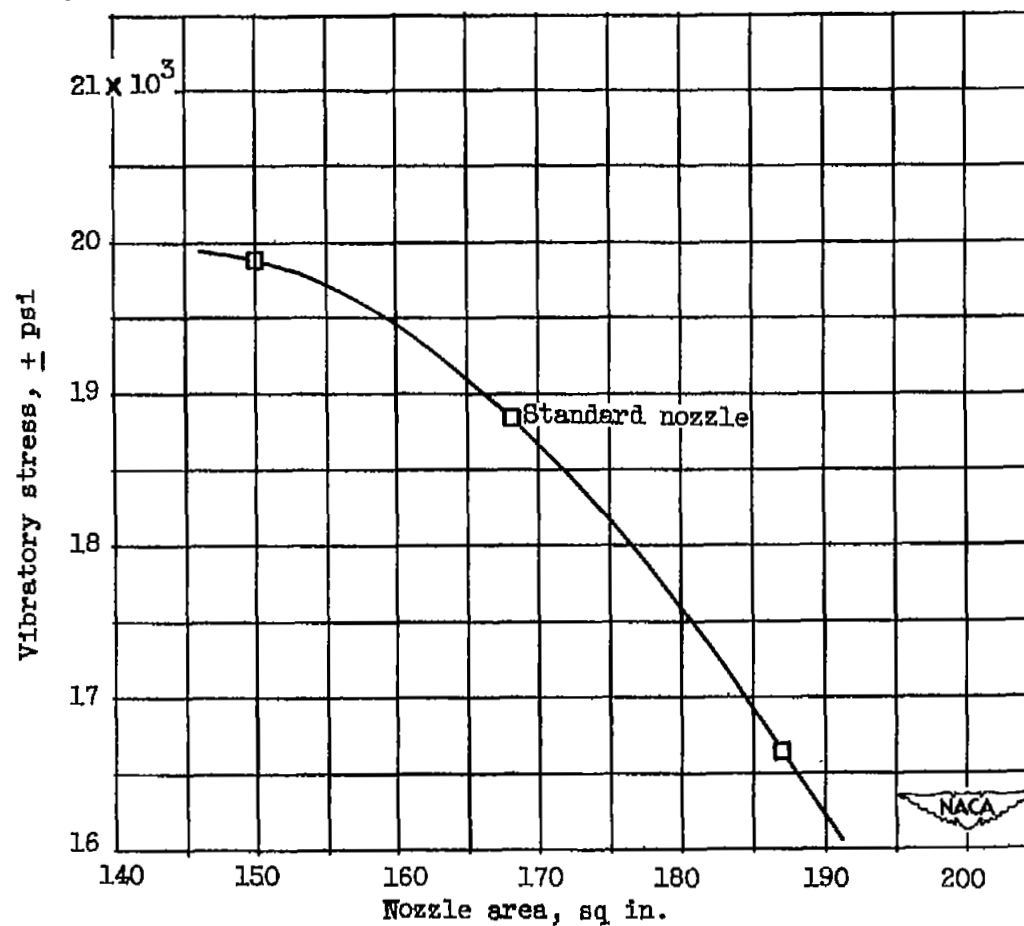


Figure 6. - Effect of exhaust-nozzle area on vibratory stress of third-stage blade.

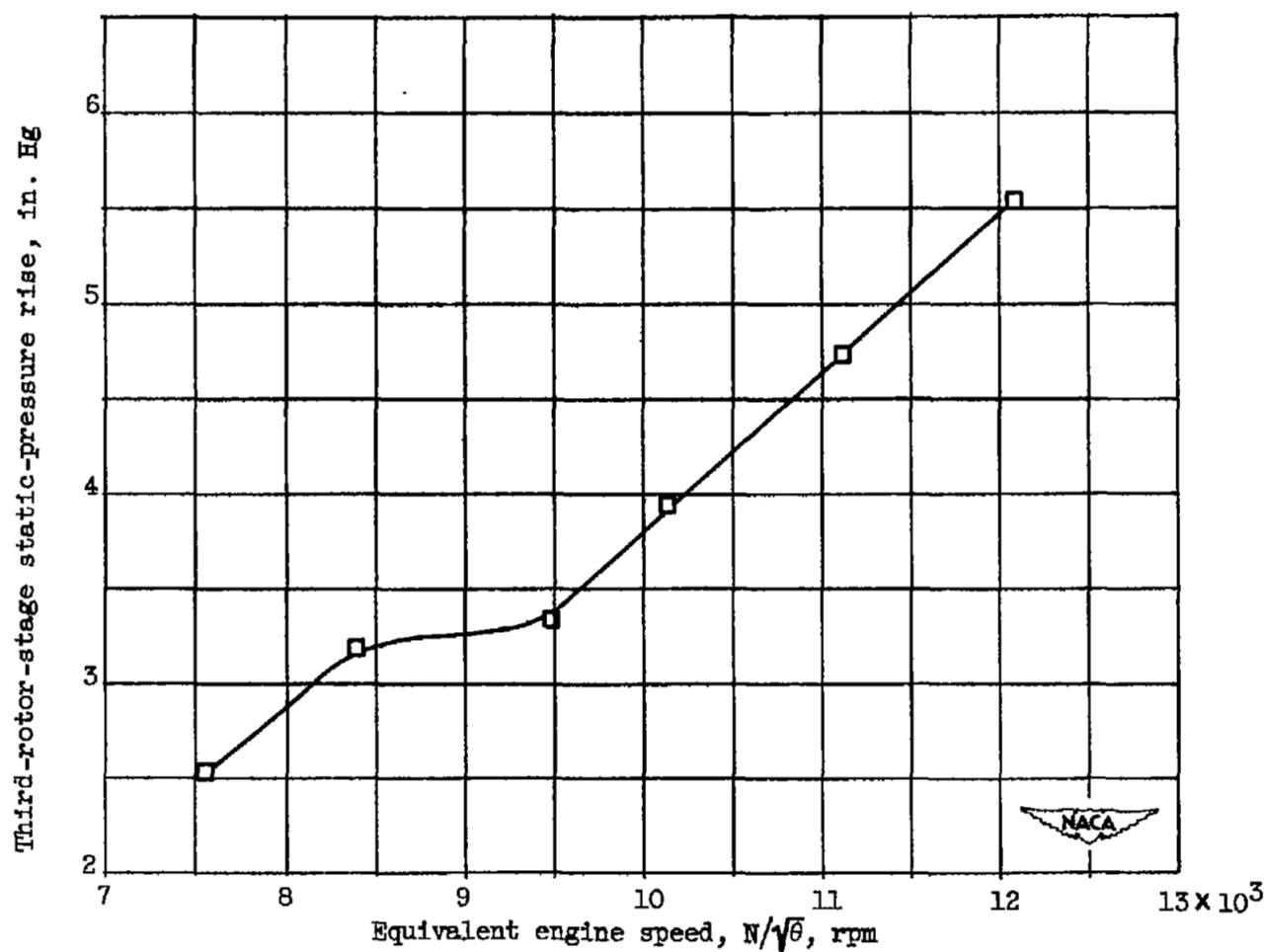


Figure 7. - Third-stage static-pressure-rise survey.

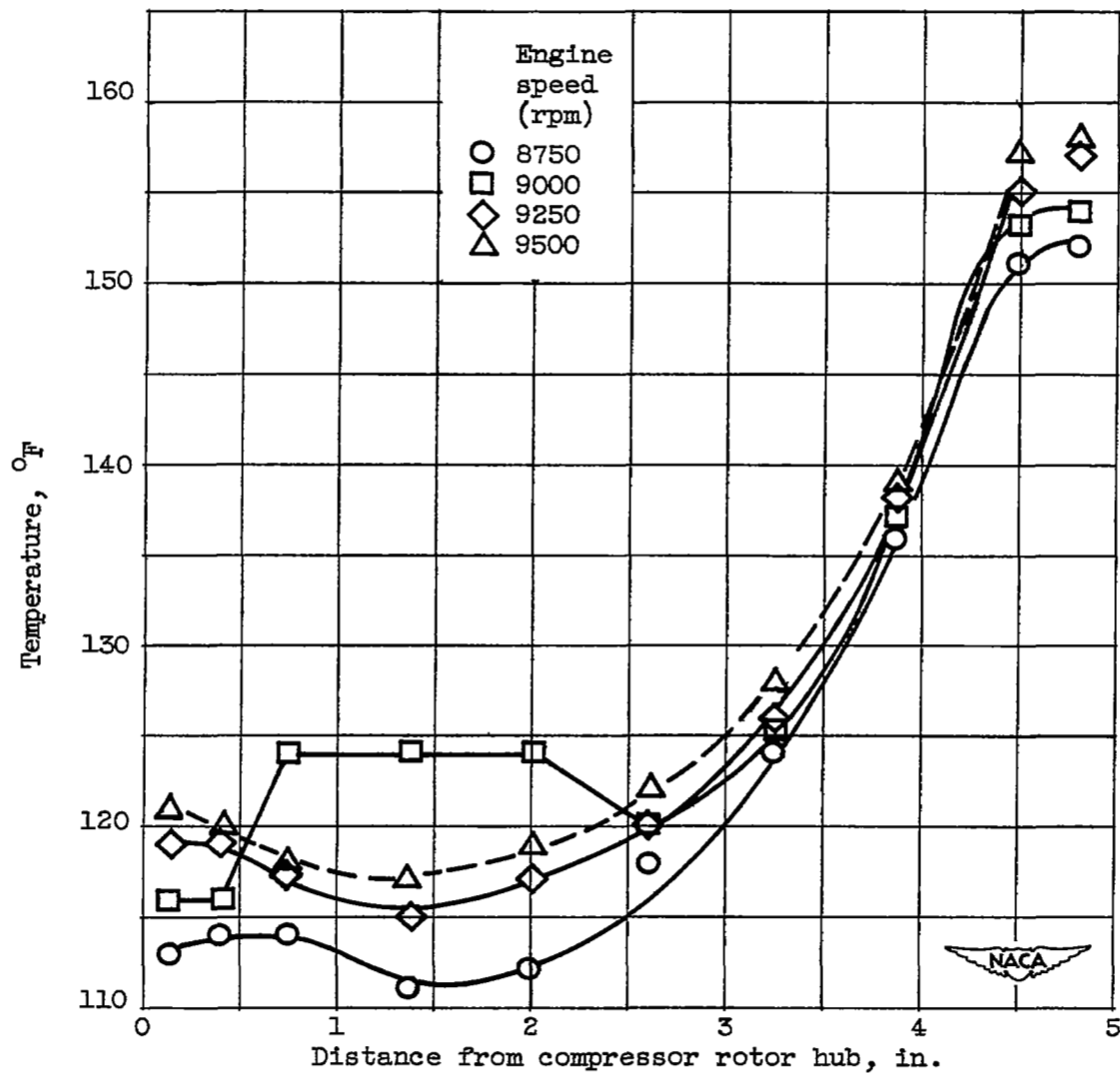


Figure 8. - Third-stage radial temperature survey.

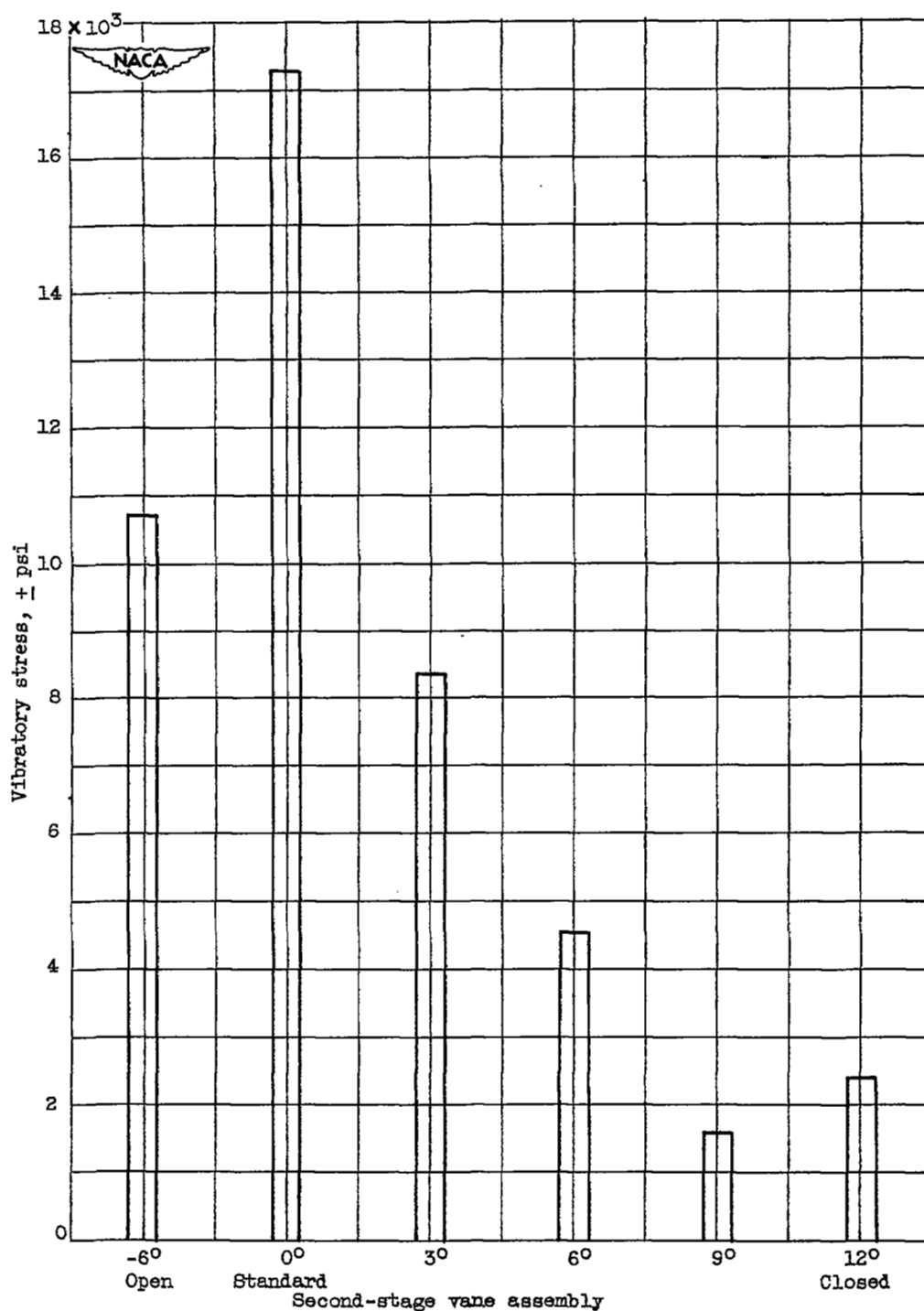
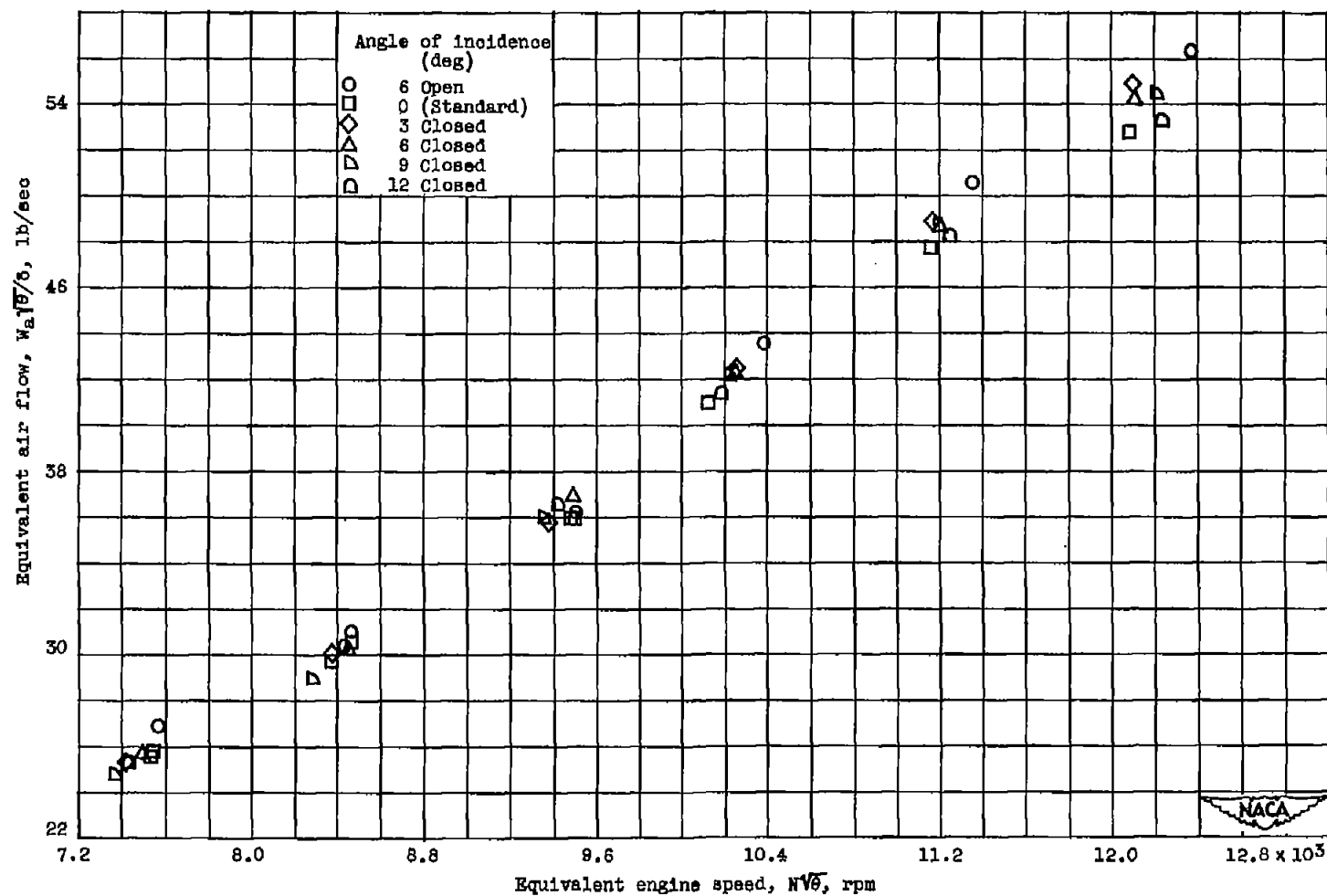
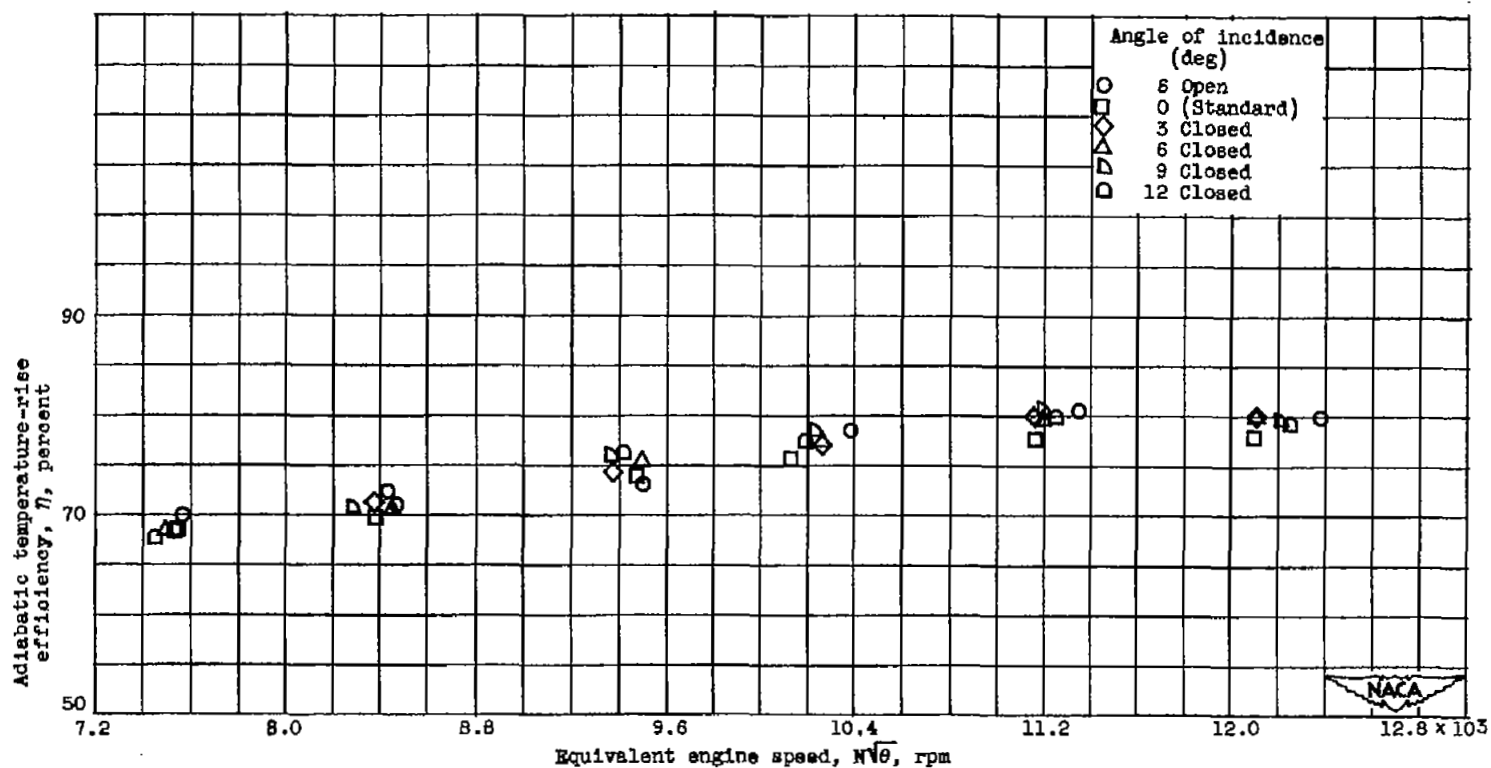


Figure 9. - Effect of second-stage vane-assembly angle of incidence on third-stage vibration.



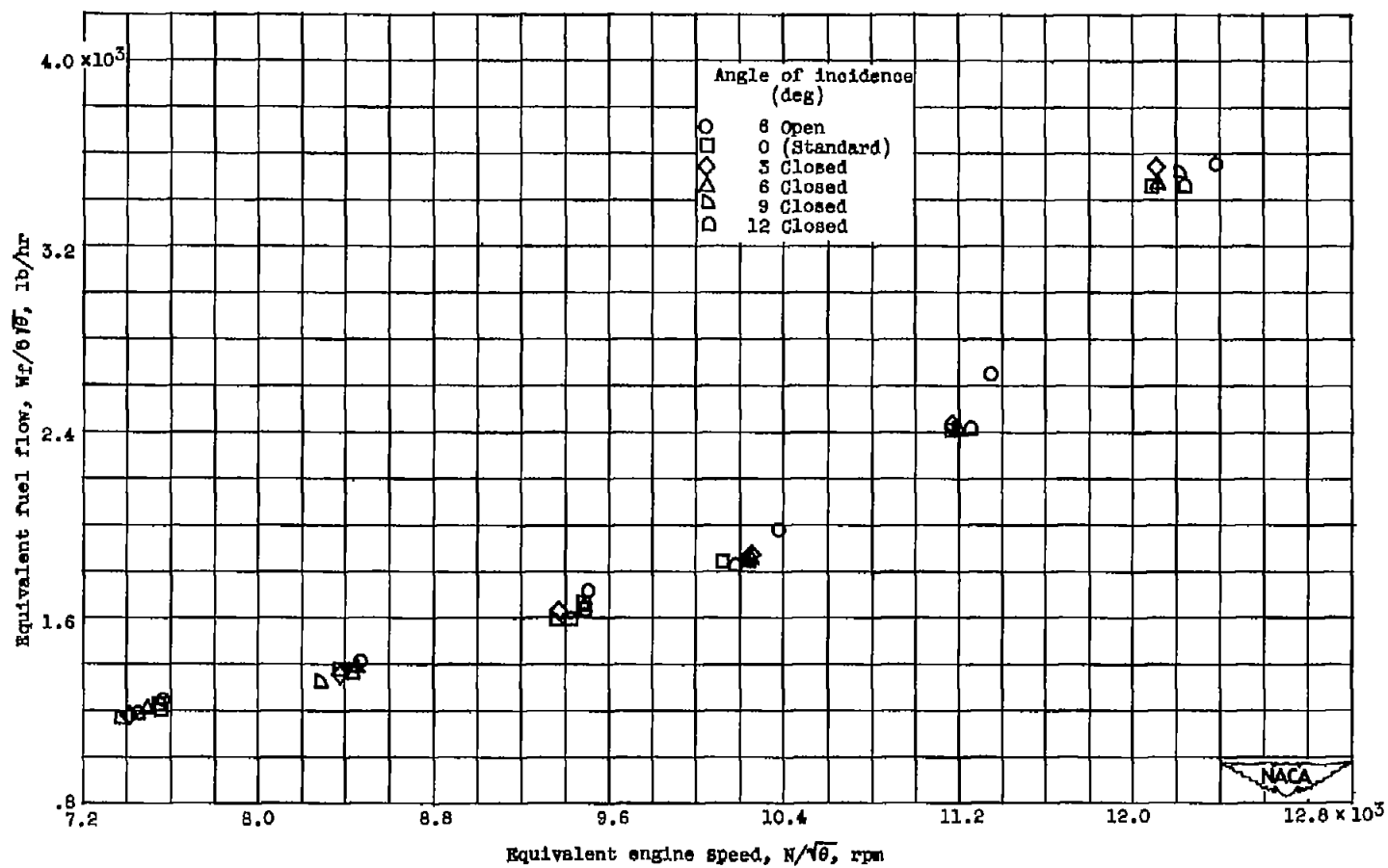
(a) Equivalent air flow.

Figure 10. - Performance characteristics of eleven-stage compressor with various second-stage vane-assembly angles of incidence.



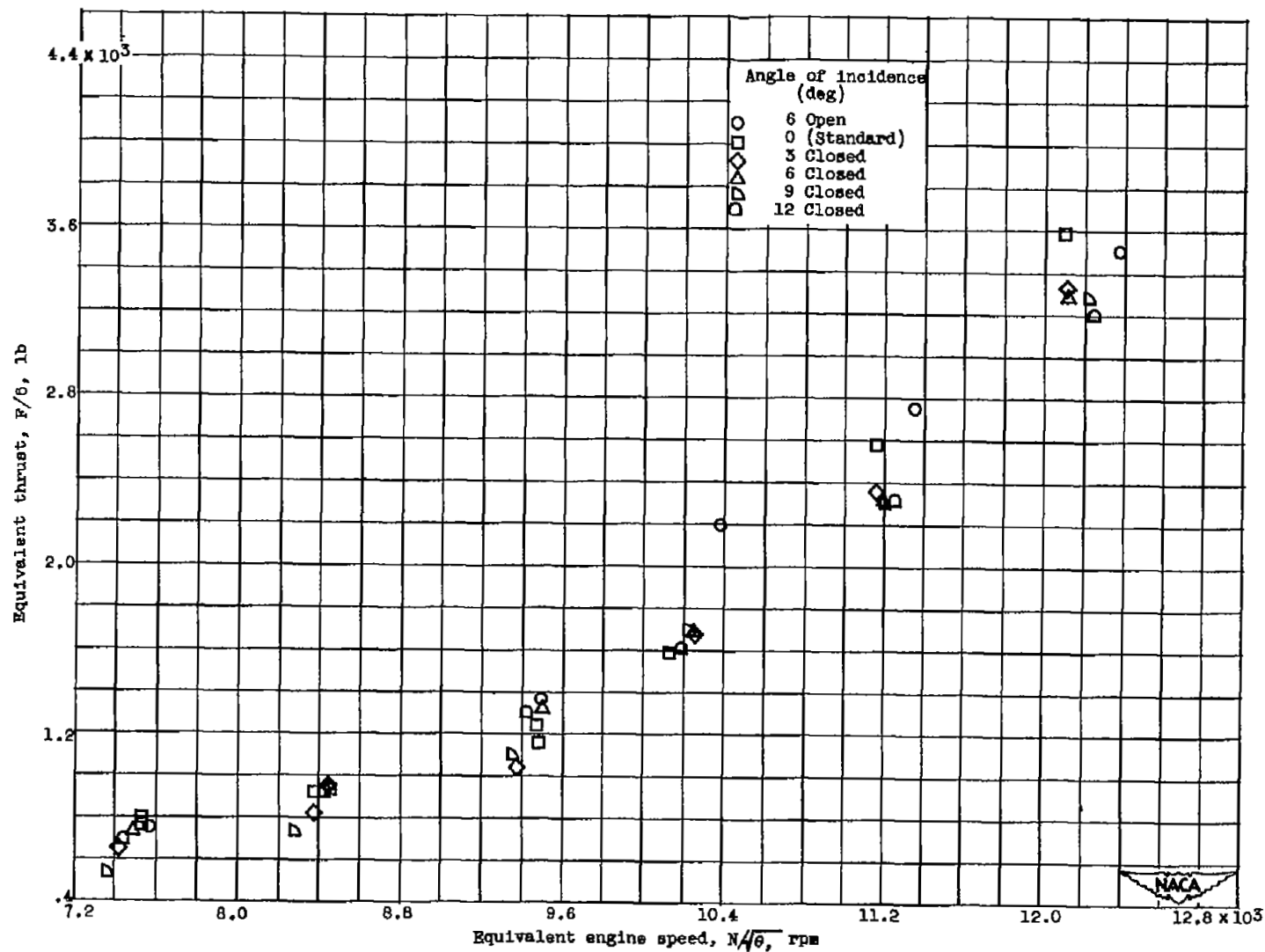
(b) Adiabatic temperature-rise efficiency.

Figure 10. - Concluded. Performance characteristics of eleven-stage compressor with various second-stage vane-assembly angles of incidence.



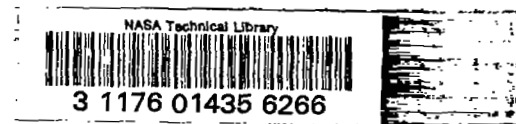
(a) Equivalent fuel flow.

Figure 11. - Performance characteristics of turbojet engine with various second-stage vane-assembly angles of incidence.



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